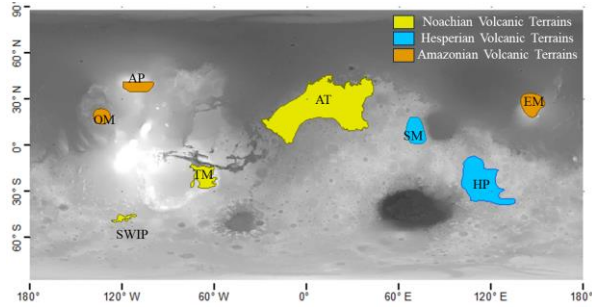


**GEOCHEMICAL INSIGHTS INTO VOLCANIC AND LITHOSPHERIC EVOLUTION OF MARS.** A. Rani<sup>1,2\*</sup>, A. Basu Sarbadhikari<sup>1</sup>, Y. Srivastava<sup>1</sup>, L. Ojha<sup>3</sup>, Heidi F. Haviland<sup>4</sup>, and S. Karunatillake<sup>5</sup>, <sup>1</sup>Physical Research Laboratory, Navrangpura, Ahmedabad, India; <sup>2</sup>NASA Post-doctoral Program Fellow, Marshall Space Flight Center, Huntsville, AL, USA (alka.rani@nasa.gov); <sup>3</sup>Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, USA; <sup>4</sup>NASA Marshall Space Flight Center, Huntsville, AL, USA; and <sup>5</sup>Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, USA

**Introduction:** The Martian lithosphere plays a pivotal role in volcanic processes, altering surface features, climate shifts, and the planet's early habitability. Crucially, the rigid lithosphere significantly influences Mars' long-term thermal conditions. Studying various geological eons' volcanic compositions unveils how the lithosphere has evolved, even though understanding the early Noachian volcanic chemistry remains challenging due to weathering and resurfacing.

In this study, newly discovered Noachian volcanic terranes [1-2] along with Hesperian and Amazonian volcanic terranes [3] are considered (*Figure 1*), to infer the evolution of the Martian lithosphere.



*Figure 1: Mars topographic map derived from MOLA-HRSC data [4] highlights the study regions including the Noachian volcanic terranes, Arabia Terra (AT), Thaumasia Minor (TM), and the Southwest Margin of Icaria Planum (SWIP) [5]. Additionally, the Hesperian volcanic terranes such as Syrtis Major (SM), Hesperia Planum (HP), and, the Amazonian volcanic terranes encompass Elysium Mons (EM), Alba Patera (AP), and Olympus Mons (OM) are marked.*

**Methods and Datasets:** We use the most recent elemental mass fraction maps derived from gamma spectroscopy data from the Mars Odyssey 2001 mission [6] to ascertain the bulk composition of the Martian landscape. Utilizing the updated geochemical provinces dataset of Mars [7], we consider bulk chemistry variations within our study regions. The maps, at a resolution of  $5^0 \times 5^0$ , encompass elements like Al, Ca, Fe, Si, K, Th, H<sub>2</sub>O, Cl, and S, detected through Gamma-Ray

Spectroscopy (GRS) with decimeter scale depth sensitivity [6].

Additional major and minor elements like Mg, Na, Ti, P, and Mn, using mass balance methods [8] serve as inputs for melting and crystallization simulations. We employ the pMELTS model with FMQ-3 to FMQ oxygen fugacity to estimate the Pressure ( $P$ ) and melting degree ( $F$ ) in various eons of volcanic terranes. We have also used conventional thermobarometric calculations to determine their formation  $P$ - $T$  conditions, using silica activity and olivine-melt Mg-exchange thermometry [9-10].

## **Results: Chemical Composition of Studied Volcanic**

**Terranes:** To find the formation  $P$ - $T$  conditions of the studied volcanic samples, it is necessary to understand whether the measured composition represents a parental melt composition in chemical equilibrium with the mantle source or not. Therefore, we have investigated if GRS-derived compositions signify primary igneous processes by evaluating weathering through the Chemical Index of Alteration (CIA), K/Th ratios, and ternary plots for aqueous alteration. Consistent K/Th ratios with average Martian crust composition and low CIA ( $<50$ ) and overlapping of studied volcanic composition with meteorites in ternary plots across volcanic regions suggest minimal weathering over a regional scale, affirming well-preserved igneous material extending at decimeter depths. In addition, the calculated bulk compositions align with Martian mantle equilibrium, confirming studied volcanic terranes - Arabia Terra, Thaumasia Minor, and SWIP - as primary or less altered compositions, reinforcing their representativeness at a regional GRS scale on Mars. We have also estimated the bulk compositions of Hesperian and Amazonian volcanic terranes shown in *Figure 1*. All volcanic terranes represent the primary or minimally altered composition.

## **Temporal Evolution of Martian Volcanic Terranes:**

Our results show  $P$ - $T$  conditions ranging from 1.3-1.6

GPa and 1340-1390°C for Noachian terranes, while Hesperian volcanic terranes vary from 1.6-1.7 GPa and 1360-1400°C, and Amazonian volcanic terranes range between 1.9-2.8 GPa and 1370-1435°C. Using calculated  $P$ , we have estimated the depth of melting/lithospheric thicknesses which range from 125-145 km for Noachian terranes, 145-150 km for Hesperian terranes, and 195-260 km for Amazonian terranes. Partial melting percentages ( $F$ ) range from 8-12% for Noachian, 10-11% for Hesperian, and 10-12% for Amazonian. We have also calculated mantle potential temperatures ( $T_p$ ) to show variations across eons (Figure 2). Heat flux estimation shows variations from 51-68 mW/m<sup>2</sup> for Noachian, 43-45 mW/m<sup>2</sup> for Hesperian, and 27-41 mW/m<sup>2</sup> for Amazonian terranes, implying temporal changes in lithospheric thickness and heat flow. Comparison of Noachian volcanic terranes with Hesperian and Amazonian reveals variations in lithospheric thickness and heat flux, indicating implications for Martian surface conditions, including volcanic activity, and climatic evolution via degassing which might affect the early habitability.

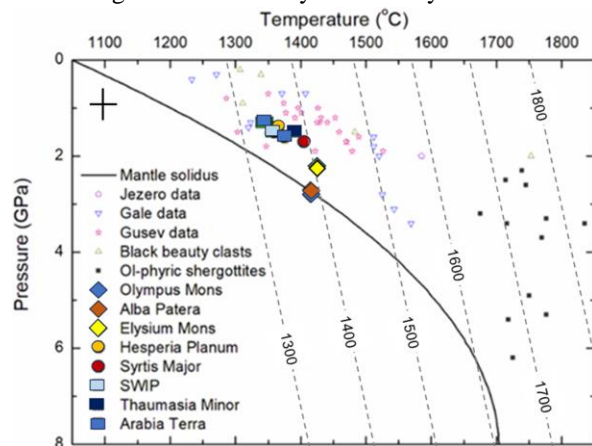


Figure 2:  $P$ - $T$  diagram displays formation conditions of studied Martian volcanic regions using GRS data, alongside Noachian-age surface basalt samples from Gusev, Gale, and Jezero. Dashed lines represent Martian mantle potential temperatures, calculated by adding the latent heat of fusion to the equilibrium temperature at which melt and solid mantle coexist and subtracting the Martian adiabatic gradient corresponding to the depth of melt. The solid line shows the Martian mantle solidus [11].

**Discussion & Implication:** The study explores Martian volcanic activity and lithospheric evolution across eons. Relative to the Amazonian terranes lithospheric

thickness from the Noachian to Hesperian eons is less and uniform suggesting persistent weak/shallower plumes with frequent eruption until Hesperian leads to more degassing. Whereas, fewer, deeper-origin plumes dominated during the Amazonian eons with lower heat flux, indicating a more evolved mantle relatively less degassing. The research also highlights the significance of volcanic degassing in Mars' early history. This process played a crucial role in shaping the planet's climate by potentially sustaining water on the surface and influencing warm-wet or cold-dry conditions. Understanding these conditions is crucial not only for scientific exploration but also has great potential implications for astrobiological research, expanding perspectives for future Martian missions.

**Future work:** As volcanism was active throughout its history. The emergence of Mars' extensive volcanic regions, known as large igneous provinces, which are linked to intermittent volcanic activity driven by mantle plumes, poses challenges to understanding the scale and persistence of these phenomena in Martian convection models. Therefore, understanding the regional-scale changes in eruptive processes within Martian volcanic provinces over time remains unclear and crucial for deciphering the evolution of the Martian interior without Earth-like plate tectonics. We will continue this work with petrological and thermoelastic analyses to study the compositional and spatiotemporal evolution of the Elysium Volcanic Province.

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